REPORT No. 294

THE MEASUREMENT OF MAXIMUM CYLINDER PRESSURES

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SUMMARY

The work presented in this report was undertaken at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics to determine a suitable method for measuring the maximum pressures occurring in aircraft engine cylinders. The study and development of instruments for the measurement of maximum cylinder pressures has been conducted in connection with carburetor and oil engine investigations on a single cylinder aircraft-type engine. Five maximum cylinder-pressure devices have been designed, constructed, and tested, in addition to the testing of three commercial indicators.

Values of maximum cylinder pressures are given as obtained with various indicators for the same pressures and for various kinds and values of maximum cylinder pressures, produced chiefly by variation of the injection advance angle in a high-speed oil engine. It is the high pressure of short duration that is most difficult to measure, because the time of its duration is so short that little work can be done to operate an indicator.

The investigations conducted thus far indicate that the greatest accuracy in determining maximum cylinder pressures can be obtained with an electric, balanced-pressure, diaphragm or disk-type indicator so constructed as to have a diaphragm or disk of relatively large area and minimum seat width and mass.

INTRODUCTION

The problem of designing and developing instruments for measuring and recording the maximum pressures within the cylinders of high-speed internal-combustion engines requires a considerable amount of research work. There is little accurate information available, at present, on the rate of rise, intensity, and duration of cylinder pressures. Knowledge of the intensity and character of cylinder pressures is important for two reasons. First, it is necessary in engine research to establish a limiting pressure beyond which it is not desired to operate an engine. Second, it is desirable to know the character of those pressures that affect engine life.

The types of combustion to be considered in the measurement of engine cylinder pressures are constant volume combustion, constant pressure combustion, and combinations of these two. It is possible to have a large part of the fuel charge burn at practically constant volume in either the carburetor engine or the high-speed oil engine. With suitable conditions, as in slow-speed oil-engine operation, there can be a combination of both constant volume and constant pressure combustion with a large percentage of the fuel burning at constant pressure. There may be enough constant volume combustion, however, in high-speed oil engines to require serious consideration, since it is the constant volume combustion that may give rise to excessive cylinder pressures and subsequent destruction of engine parts. As the conditions affecting combustion in the high-speed oil engine are altered, there is a change in the rate of rise and duration of the maximum cylinder pressure which brings out the limitations of the available instruments for measuring maximum pressures.

The maximum cylinder pressure indicators now available may be classified under two types. One type makes use of the cylinder pressure in recording directly—that is, all the work of recording is done by the gas in the cylinder. The other type uses the cylinder pressure to operate only an auxiliary part of the recording apparatus.

The material for this report has been obtained in connection with various carburetor and oil-engine investigations (References 1 and 2) made with a N. A. C. A. Universal test engine (Reference 3) at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics. The study and development of instruments for the measurement of cylinder pressures has been conducted in connection with engine tests in an effort to obtain accurate cylinder-pressure data, and was not carried on as a separate research. Five instruments for indicating maximum cylinder pressures have been designed, constructed, and tested at this laboratory in addition to the testing of three commercial indicators.

METHODS AND APPARATUS

The maximum cylinder-pressure indicator shown in Figure 1 is of the type that receives all the energy for its operation from the cylinder gases. The working parts of this indicator consist of a spring-loaded piston exposed to the cylinder pressure and a pointer operated by the piston and indicating its movement. The procedure in taking a reading is to allow the piston to move

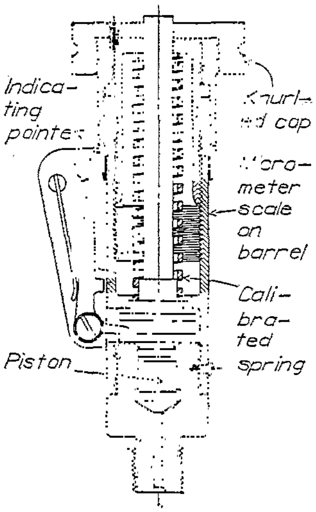

FIG. 1.—Piston type maximum pressure indicator

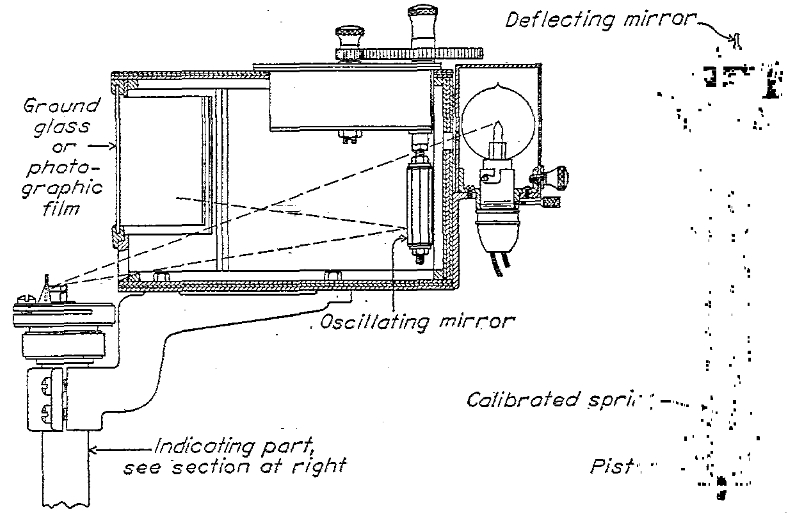

FIG. 2.—Optical type indicator

with each explosion and then screw down the knurled cap until the spring tension is just sufficient to stop any piston movement. At this point the spring tension, friction, and the inertia of the moving parts just balance the force of the maximum cylinder pressure.

The indicator shown in Figure 2 is of the same type as that shown in Figure 1. This instrument is designed to operate with a small piston movement which is magnified by means of a reflected light beam. Cylinder pressures are recorded throughout the engine cycle by reflecting a beam of light onto a ground glass or photographic film by means of a mirror directly connected to the operating piston by a tie rod and pivoted arm. A driving mechanism which operates an oscillating mirror in synchronism with the engine may, at the discretion of the operator, cause the light beam to trace either a pressure-volume or a pressure-time card.

The instrument shown in Figure 3 was designed to aid in detecting detonation by means of a diaphragm exposed directly to the rapidly varying cylinder pressure and communicating the resultant pressure wave through water to a telephone diaphragm. The carbon pile indicator, shown in Figure 4, was also designed to aid in detecting detonation. In this instrument the diaphragm was exposed to the water in the cylinder-head jacket and a direct mechanical connection was made with a carbon pile. The assumption was that the detonation pressures would transmit a shock wave to the water around the cylinder head with sufficient force to move the diaphragm and compress the carbon pile. The carbon pile was later connected in series with an external electric circuit that included head phones.

The "bouncing pin" method of measuring detonation was tried under conditions of variable compression ratio and combustion characteristics. This instrument, as shown in Figure 5, has a pin resting freely on a piston element. Contact points are held in position in an electrical circuit by springs, in such a way as to be closed when the bouncing pin is thrown free of the

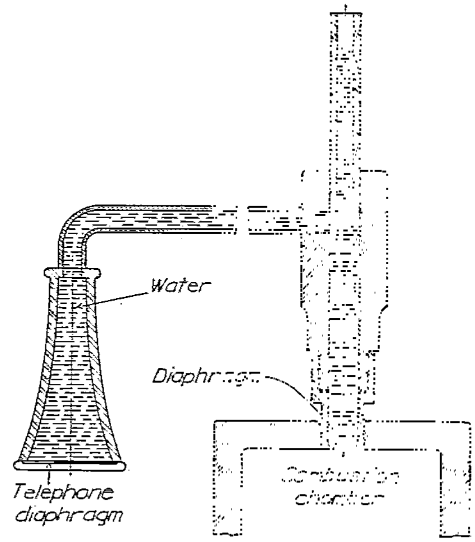

Fig. 3.—Detonation detector

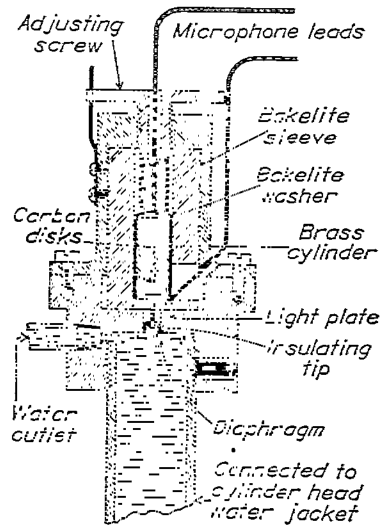

Fig. 4.—Carbon-pile pressure indicator

piston. It is assumed that the amount of throw is proportional to the intensity of the detonation pressure, and the total length of time the contact points are closed, during a test period, is obtained by measuring the volume of gases generated from the electrolysis of a quantity of acidulated water placed in series with the contact points.

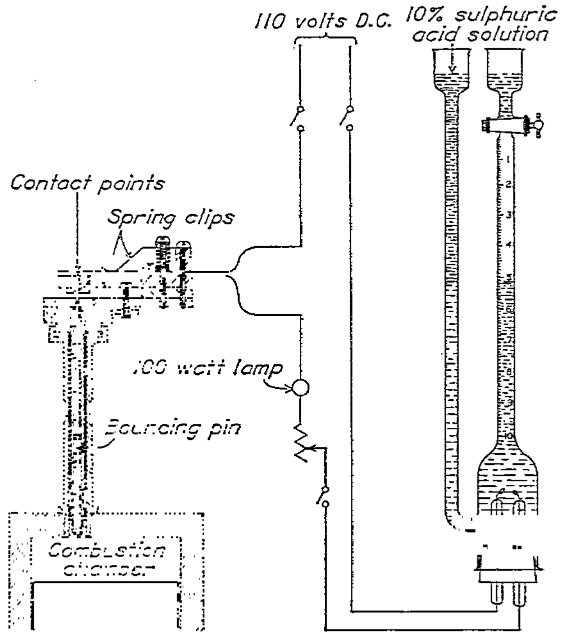

Fig. 5.—Bouncing-pin detonation meter

The indicator shown in Figure 6 was designed for the recording of maximum cylinder pressures by the balanced pressure method. The ball check valve was later replaced by a more sensitive disk-valve as shown in Figure 7. Both "balanced" and "trapped" pressures were recorded with this disk-type indicator. In recording by the balanced pressure method an auxiliary air-pressure tank is used to insure pressure in excess of the cylinder pressure to be measured. This air pressure is admitted to the outer side of the disk and so regulated that the maximum cylinder pressures are balanced as indicated by a pressure gauge needle. The gauge needle will fluctuate when the external pressure is less than the maximum cylinder pressure,

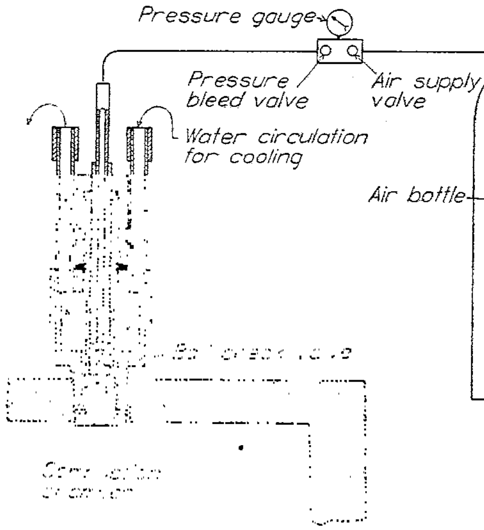

FIG. 6.—Ball check maximum pressure indicator

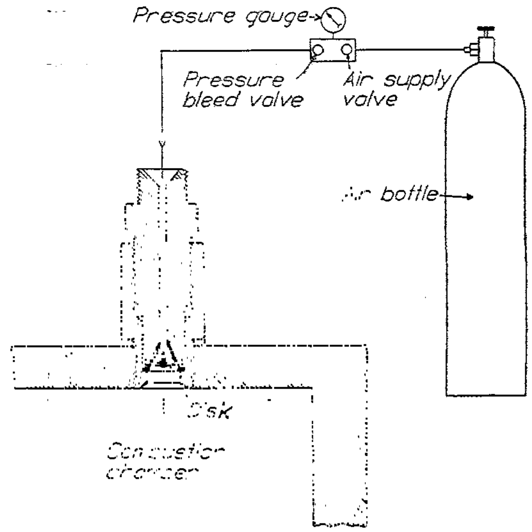

FIG. 7.—Disk-valve maximum pressure indicator

for there will be a pressure wave produced in the line when the disk is just lifted from its seat. In the trapped pressure method the gas in the engine cylinder is allowed to lift the disk and some of the gas that passes through the seat is trapped above the disk when it reseats. The principle of operation is that of a one-way, automatic, by-pass valve. There is, therefore, a pressure built up in the external line in communication with the pressure gauge which is lower than but indicates the maximum cylinder pressure.

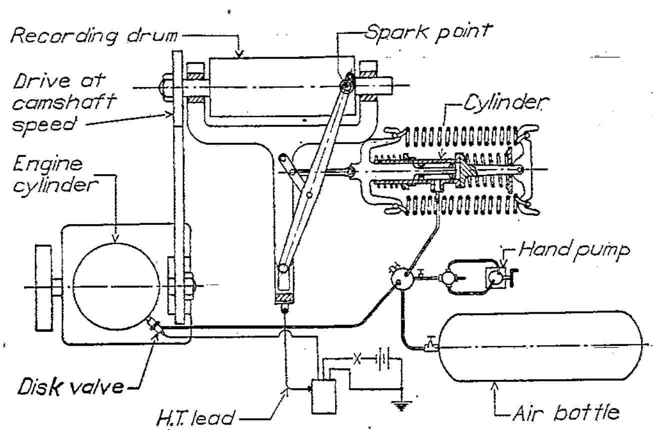

FIG. 8.—Electrical balanced pressure disk type indicator

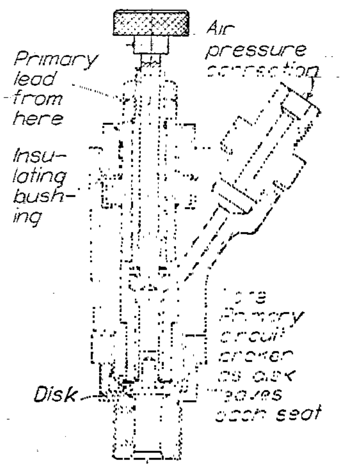

FIG. 9.—Electrical balanced pressure disk valve

An electric type pressure indicator is shown in the diagrammatic drawing in Figure 8, and the balanced disk valve used with this indicator is shown in cross section in Figure 9. This instrument is an example of the type that uses the energy of the cylinder gases to operate only a small part of the recording mechanism. Air under pressure is admitted to the disk valve and also to the recording drum mechanism. A spring-constrained piston in the latter moves a sparking point in straight-line motion along the recording drum. This drum carries a record paper and is driven by the engine at cam-shaft speed. The disk of the valve is exposed on the underside to the engine cylinder pressure and moves from one seat to the other as the cylinder pressure and the external pressure alternately become greater. This disk acts as a breaker point for an electrical induction system, and as it leaves each seat a spark is caused to jump from the spark point to the recording drum and perforate the paper. When the controlled external pressure is varied over the complete range of engine cylinder pressures a pressure-time card is recorded representing the average of many cycles.

The audible manifestations of high cylinder pressures, such as those produced by detonation give a means of comparing pressure values directly by the ear. It is possible, with training, to separate the detonation sound from other engine noises, but the personal rating of the intensity of the sound is far from being accurate.

DISCUSSION AND ANALYSIS OF RESULTS

The main source of error found in the use of the maximum pressure indicator shown in Figure 1 are the inertia of moving parts, piston friction, and temperature effect on the load spring. Although there is no movement of the piston at the time of recording with this indicator, the inertia and friction forces are present to prevent movement and cause inaccurate settings to be made. The same sources of error are present with the optical indicator of Figure 2, but the errors may be reduced because of continuous movement of the piston throughout the cycle and the small amount of piston displacement required to produce a large scale indicator card.

The detonation detector shown in Figure 3 did not transmit a sound that could be distinguished from other engine noises. Mechanical vibrations and temperature effect on the indicator parts prevented any consistent checking of the results with the indicator shown in Figure 4. In addition to the attempt to record the current fluctuations in the external line, a set of head phones was connected in series with the carbon pile in an effort to obtain an audible "click." The "clicks" heard in the head phones were independent of the cylinder pressures, and any audible sounds produced by the head phones during detonation were also present when the engine was not detonating.

The "bouncing pin" detonation meter shown in Figure 5 did not give consistent results over a range of variable compression ratios. While this method of detecting detonation may give comparative results at a low compression ratio, it does not give a true indication of the cylinder pressure involved. It was possible, at engine speeds of 1,500 R. P. M., to make the pin bounce and record by compression alone when the compression ratio was raised above 7.3.

The indicators operating with check valves have given consistent readings when used for recording by both the balanced and trapped pressure methods. The ball check valve shown in Figure 6 required a seat width that introduced errors due to the difference in the area exposed to the cylinder pressure and the balancing pressure. Balanced pressures have been recorded quite accurately with the disk valve shown in Figure 7. The disk of this valve has a large area exposed to the cylinder pressures for its mass, and has a seat width of less than 0.005 inch. The greatest error introduced with this instrument is in observing or obtaining similar small fluctuations of the Bourbon gauge needle in all tests just before they are damped out.

The commercial, electric, balanced-pressure indicator (fig. 9) has a disk-seat width of 0.034 inch, which gives incorrect readings, because of the different areas exposed to the cylinder and balancing gas pressures. With an air pressure of 700 pounds per square inch holding the disk on its seat, a cylinder pressure of 935 pounds per square inch is required to equalize the force on the disk and cause it to record. Even though the disk of this indicator has excessive seat width and mass the recording of maximum cylinder pressures has been consistent and corrections and alterations may be made to improve its performance, such as replacing the disk with a thin diaphragm clamped at its outer edge between two perforated supports to limit its displacement. (Reference 4.) This method of operating the electric circuit-breaker mechanism will greatly reduce the inertia of the indicator parts.

Curves of brake mean effective pressure and the corresponding maximum cylinder pressure as recorded by the balanced-pressure method and the trapped pressure method with the disk valve shown in Figure 7 are given in Figure 10. The compression pressures were 350 pounds per square inch and 560 pounds per square inch and the engine speed was 1,500 R. P. M. The difference in compression pressure caused a difference in combustion and provided a means for comparing the two methods of measuring maximum cylinder pressures. It may be noted that the pressures recorded are not in accordance with the brake-mean effective pressure. At 350 pounds compression pressure there was less heat for the preparation of the fuel, and therefore more fuel was burned at constant volume with a resultant high maximum cylinder pressure as evidenced by the high B. M. E. P. and sound of the combustion knock. Because of the poor penetration of the fuel at the high-compression pressure, all injection conditions being maintained constant, the brake mean effective pressure is low, but there is more constant pressure combustion and a slower pressure rise which gives a higher maximum pressure reading.

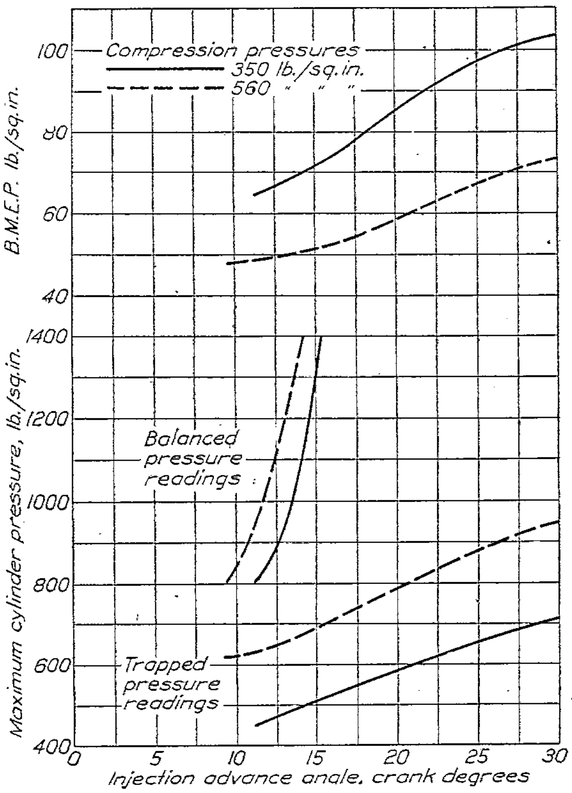

FIG. 10.—Comparison of the cylinder pressures recorded by the disk-valve of Fig. 7. Universal test engine, oil engine operation, 1,500 R. P. M., with fuel quantity and operating temperatures maintained at constant values

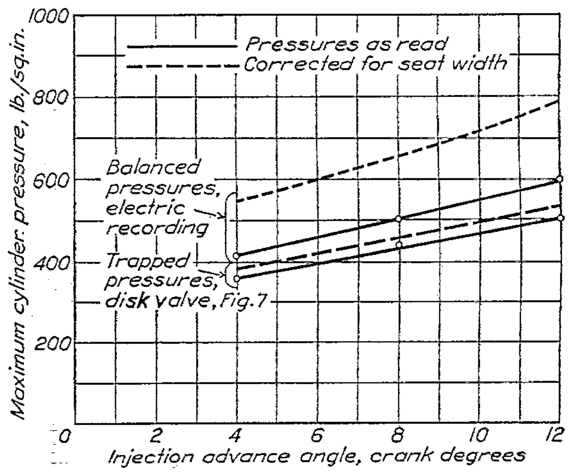

FIG. 11.—Effect of disk seat width on the recording of cylinder pressures by the disk-valves of Figs. 7 and 9. Universal test engine, oil engine operation, 1,500 R. P. M., with fuel quantity, compression ratio, and operating temperatures maintained at constant values

A fast rising pressure with a high maximum value of short duration does not have time to do the necessary work on the disk to record, whereas a slow pressure rise with a low maximum pressure will record a relatively high pressure. The trapped pressure readings are too low, because the cylinder gas must lift the disk and enter the valve against the existing trapped pressure. The balanced-pressure readings are probably a better indication of the true pressures, for only the inertia of the light disk and sensitivity of the gauge must be accounted for in the actual movement of the indicating mechanism.

The effect of seat width on pressure recording by a balanced-pressure disk valve is shown in Figure 11. For these tests the conditions of engine operation were maintained constant, which should give approximately the same maximum cylinder pressures to record. The trapped pressures were recorded by the disk-valve indicator of Figure 7, and the electric recording was done by the electrical, balanced-pressure indicator of Figure 9. The dotted curves give cylinder pressures corrected for the effect of differential disk-pressure area produced by the seat widths. The electric recording gives higher values than those recorded by the trapped-pressure method, because it is only necessary that the disk leave its seat to record.

The effect of the mass of the disk on the recording of cylinder pressures, as represented by the area-weight ratio, is shown in the curves of Figure 12. As in the tests shown in Figure 11, the engine-test conditions were maintained at constant values. The readings were made by the balanced-pressure method with the valves of Figures 7 and 9, the disks of which had area-weight ratios of 0.475 and 0.0957, respectively. Corrections were made for the seat widths in each instrument so that the pressure differences between the two curves in Figure 12 indicate the effect of the inertias of the disks.

The type of maximum pressure indicator using the pressure itself to do all of the work of recording, has an inherent disadvantage, because it can not respond to rapid variations of

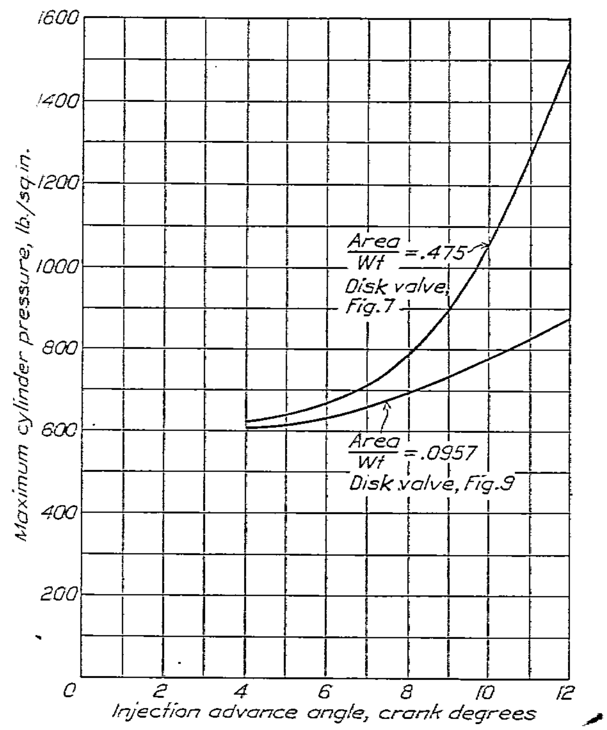

FIG. 12.—Effect of the mass and area of the valve disk on the recording of cylinder pressures by the valves of Figs. 7 and 9. Universal test engine, oil engine operation, 1,500 R. P. M., with fuel quantity compression ratio, and operating temperatures maintained at constant values

pressure. It must absorb a definite amount of energy from the cylinder pressure to overcome large inertia forces, and, since the time rate of pressure rise is variable, it is difficult to attempt a correction for this loss.

In some instruments the inertia of the moving parts or the movement of these parts is reduced to a small value, but this only reduces the error and does not give accurate results or an accurate method for making a correction. With the type of instruments using the cylinder pressure to operate only a small part of the recording mechanism, the error is reduced and may lead to the elimination of enough variables so that more accurate corrections can be made.

The human ear has been used for indicating the approximate intensity of maximum cylinder pressures. Although the personal rating of sound intensity is not considered reliable, the point at which detonation becomes audible may be checked with a fair degree of accuracy. The high-pressure "pink" of detonation has a sound frequency much different from the noise of valve gears, tappets, rocker arms, and other moving engine parts. An observer, accustomed to listening to detonation, may have his ear trained so that he can distinguish a high-pressure knock even though it be of less intensity than other engine noises.

In analyzing the destructive power of cylinder pressures there are three characteristics which must be considered—the cylinder pressure attains a certain force value, it attains this value in a definite time, and the pressure is maintained a definite length of time. The ability of the cylinder gas to do work on the indicator is a function of force and time. The work done by the cylinder pressure may be separated into the useful work done on the piston as mean effective pressure and the destructive work. If the maximum cylinder pressure is of too short duration it can do little useful work. The pressure may be of sufficient duration, however, to cause a deflection of the cylinder and cylinder head with enough movement to set up a sound wave. This deflection need not be much when it is realized that the amplitude of sound waves in air, audible to the human ear, range from 5.0×10^{-8} to 4.0×10^{-3} inch. (Reference 5.) The detonation "pink" of the carburetor engine is the manifestation of an extremely high and fast-rising pressure of short duration. This type of pressure rise delivers a blow to the piston and cylinder head; and, if its force is sufficient to stress the metal beyond its fatigue limit, repeated stressing will cause failure. The detonation pressure is also accompanied by a high temperature that may cause trouble in engine operation.

It was noted during certain tests that the sound-wave frequency of the knock changed with a change of compression ratio and subsequent change of combustion characteristics. An adjustable tuning fork was used for comparing the sound of the engine knock with a known frequency. With a compression ratio of 14.4 and oil injection, the sound frequency of the knock was checked as being approximately 200 vibrations per second. It was noted that as the compression ratio was lowered to 10.2 the frequency of the sound wave increased. At a still lower compression ratio—i. e., 6.0—a check on the carburetor engine "pink" gave a frequency of approximately 2,000 vibrations per second. During the change in compression ratio from 14.4 to 10.2 there was a change in the combustion characteristics and subsequent rate of pressure rise. The high compression ratio and the standard conditions of engine operation gave a maximum amount of constant pressure combustion accompanied by a slow rate of pressure rise. With the low compression ratio there was a maximum amount of constant volume combustion. In the case of the carburetor engine the combustion is practically constant volume during detonation. The foregoing brief discussion on sound frequencies indicates the variable rate of pressure rise under which a cylinder pressure indicator must operate.

CONCLUSIONS

This investigation on the measurement of maximum cylinder pressures has served mainly to bring out some of the limitations of the available instruments for measuring these pressures. The main factors affecting the accuracy of the maximum cylinder pressure indicators tested are the friction and inertia of moving parts, the differential areas exposed in balanced-gas type indicators, and the short duration of the maximum cylinder pressures.

The investigations conducted thus far indicate that the greatest accuracy in determining maximum cylinder pressures can be obtained with an electric, balanced-pressure, diaphragm or disk-type indicator so constructed as to have a diaphragm or disk of relatively large area and minimum seat width and mass.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD., VA., *March 30, 1928.*

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